

Temperature-Driven Shape Changes of the Near Earth Asteroid Scout Solar Sail

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Near Earth Asteroid Scout (NEA Scout) is a NASA deep space Cubesat, scheduled to launch on the Exploration Mission 1 flight of the Space Launch System. NEA Scout will use a deployable solar sail as its primary propulsion system. The sail is a square membrane supported by rigid metallic tapespring booms, and analysis predicts that these booms will experience substantial thermal warping if they are exposed to direct sunlight in the space environment.

NASA has conducted sunspot chamber experiments to confirm the thermal distortion of this class of booms, demonstrating tip displacement of between 20 and 50 centimeters in a 4-meter boom. The distortion behavior of the boom is complex and demonstrates an application for advanced thermal-structural analysis. The needs of the NEA Scout project were supported by changing the solar sail design to keep the booms shaded during use of the solar sail, and an additional experiment in the sunspot chamber is presented in support of this solution.

Key Words: solar sailing, thermal expansion, booms, tapespring, thermal flutter

1. Introduction

This paper describes experimental work that has been done to bound thermal effects on the surface shape of an 86-square-meter solar sail in a 1 AU deep space thermal environment. The NEA Scout project [1] plans to use this solar sail as the primary propulsion system on a 6U Cubesat, with the goal of traveling to an asteroid for flyby imaging to address strategic knowledge gaps. Fig. 1 illustrates the relative scale of the 6U Cubesat and the deployed solar sail. Sail thrust control is accomplished by attitude control of the spacecraft, and the spacecraft attitude is maintained by aligning the center of mass and center of pressure. Control of the spacecraft's thrust and attitude depends upon sail flatness and global shape.

The NEA Scout sail is a thin reflective membrane supported by four deployable booms. The sail is not spin-stabilized. Metallic triangular rollable and collapsible (TRAC) booms [2], each 6.8 meters in length, are used to deploy the sail and maintain its square shape. Similar TRAC booms were used on Nanosail-D2 [3] and Lightsail-1 and -2 [4], giving this type of deployable boom some space heritage, but NEA Scout calls for longer booms than these previous missions, and also has more stringent requirements for sail functionality.

This paper presents a set of experiments that were performed

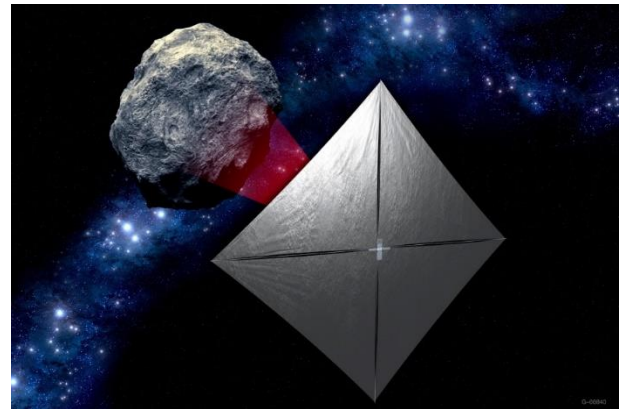


Fig. 1: Artist's illustration of NEA Scout. Note that this illustration shows an earlier, four-quadrant sail membrane, a design that was changed in response to analysis of boom thermal distortions.

to support the thermal and structural analysis of the NEA Scout mission. Using a thermal vacuum chamber with an infrared (IR) sunspot lamp, a 4-meter boom was tested in thermal conditions similar to the proposed space environment. Early analysis, briefly described in Section 2 and an earlier publication [5], motivated these experiments. The setup and data products are described in Section 3, and Sections 3.1 and 3.2 present interesting results on the behavior of the boom under thermal

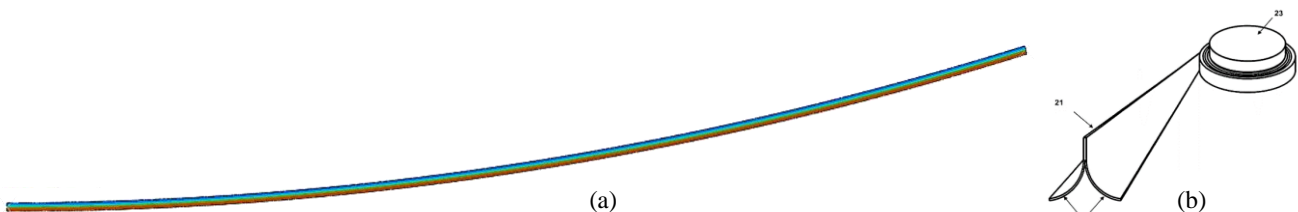


Fig. 2: The TRAC boom. (a) Analysis predicting the thermal curvature of an initially straight 4-meter Elgiloy boom at 1 AU (1:1 scale) [5] and (b) the cross-section and method of stowage.

load. A limited analysis is presented in Section 4, and the follow-up experiment in Section 4.1. The authors conclude that a tool to improve the multiphysics coupling of simulations would be invaluable.

2. Motivation and early analysis

Analysis predicted that the TRAC booms would suffer from high curvatures in direct sunlight [5]. One such prediction is shown in Fig. 2(a); the predicted boom distortion is harmful to both structural performance and surface shape accuracy. When the large magnitude of this shape change is combined with the interaction of structural forces on the gossamer sail, the shape can be unpredictable, with many tens of centimeters of shape uncertainty. Our analysis made no reliable conclusion about the relationship between the sun's angle of incidence on the sail and the sail shape; further, some predicted sail shapes put the sail's center of pressure very far from the spacecraft center of mass, producing a torque on the system that would eventually become uncorrectable.

The experiments described in this paper were designed to answer two questions: First, was thermal distortion in the booms as large as the analysis predicted? Second, would shading the booms behind the sail membrane reduce the distortion as much as predicted?

3. Experiment and results

A four-meter Elgiloy TRAC boom was tested under thermal load in the Marshall Space Flight Center Sunspot Chamber, at the Environmental Test Laboratory. Fig. 3 is a photograph of the boom installed in this thermal vacuum chamber. The chamber used an IR lamp array along the full length of the boom to apply a heat load to simulate solar heating. The IR array was turned 400 minutes into the test, after vacuum was pulled, and times in this paper are given relative to the IR array activation. The boom was hung vertically and oriented at a 45° angle to the sun lamp (Fig. 4), the angle that showed the largest thermal gradient in simulations. The chamber maintained a vacuum of 9.8×10^{-6} Tor during testing.

The boom was monitored with thermocouples (at 1 Hz) and color video (at 30 frames per second). The test was run until steady state conditions were met, defined by temperature changes of less than $\pm 1^\circ\text{C}$ per hour. Fig. 5 and Fig. 6 show the

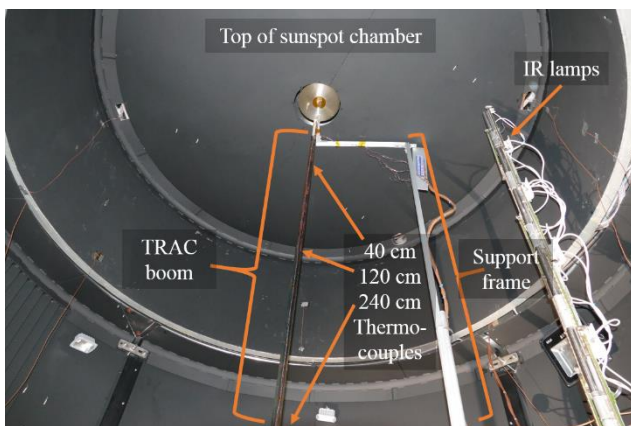


Fig. 3: The TRAC boom in the sunspot chamber.

views from the three camera positions in the unshaded experiment case. The lab coordinate system orientation is also shown in this figure. The IR lamp array is located outside the camera frame in the +X direction. The position of the boom tip was derived from this video data.

Fig. 7 shows the temperature history of several thermocouples at noted positions along the length of the boom. The steady state gradients across the booms were approximately 78°C , 76°C , and 72°C at sets of thermocouples positioned 40 cm, 120 cm, and 240 cm from the boom root, respectively.

This experiment was run only once in this “unshaded” configuration, where the boom is exposed directly to the sun lamps. A followup experiment, where a sheet a solar sail membrane material was place between the boom and lamps, was also conducted and is addressed in Section 4.1.

3.1. Static deflection and temperature history

Displacement of the boom occurred in three distinct phases: the first transitional arc of displacement (Transition 1), then a 15-minute period where the gross shape of the boom was maintained while a torsional mode was excited (Torsional motion), and finally a second transitional arc of displacement (Transition 2) to a steady-state position (End). There is no obvious explanation of what caused the boom to stop its torsional oscillation and move to a new shape and tip position, but slower changes to the shape of the support frame may have changed the illumination pattern of the boom.

The tip of the boom traced out a pattern as the boom deformed under thermal load. Fig. 8 shows the pattern of this motion, as captured by cameras 2 and 3. The positions shown in this figure should be considered to have an uncertainty on the order of 2 cm, due to uncertainties in the camera geometry. The full path was interpolated between tip positions at selected frames. This traced path was not linear and did not follow any simple pattern; further, the aluminum frame supporting the root of the boom moved in the course of the experiment. Frame motion has been subtracted from the boom root path. The total displacement of the boom tip was approximately half a meter at its most extreme deflection.

Temperature histories are consistent with the motion history of the boom, and can be summarized with a chart of the temperature gradients at different lengthwise positions on the boom. Each line in Fig. 9 shows the difference in temperature between two thermocouples. The line labeled “Delta T at 40 cm” depicts the temperature difference between two thermocouples that were located 40 cm from the root of the boom, on different parts of the boom cross-section. This station on the boom achieves a temperature difference of 120°C , which gradually drops to 80°C . In contrast, a set of thermocouples located 240 cm from the boom root rapidly swings from a difference of

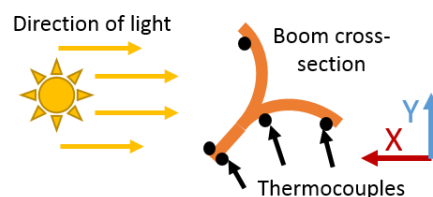


Fig. 4: Thermocouple positions within the boom cross-section at the 45° orientation.

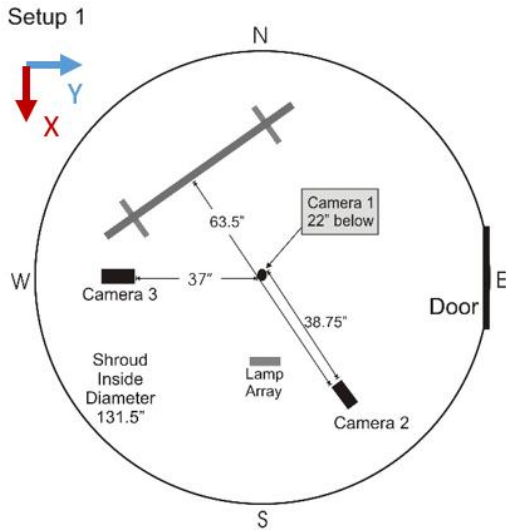


Fig. 5: The camera arrangement for the unshaded boom thermal test (view from above).

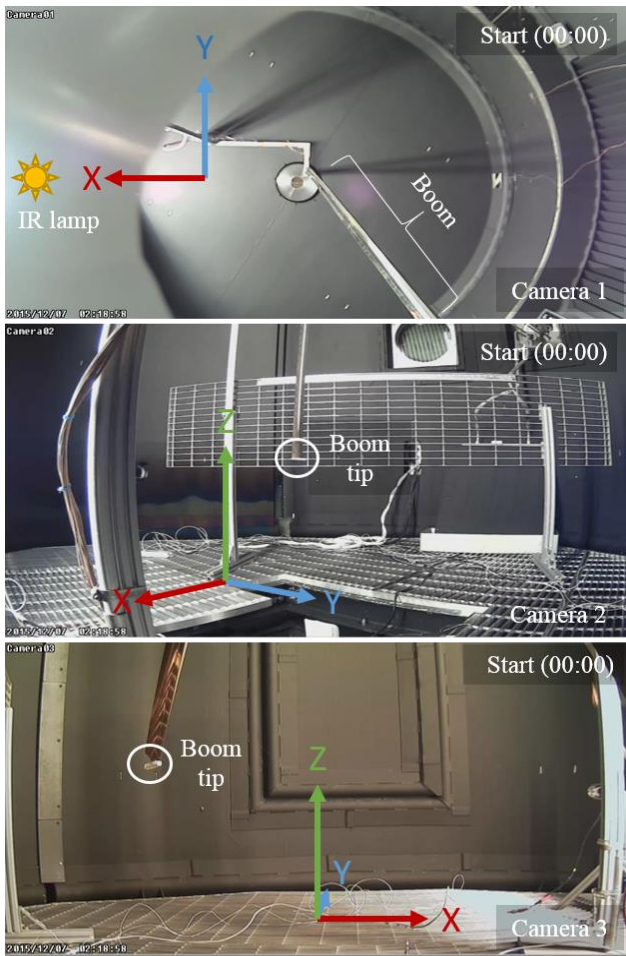


Fig. 6: The three camera positions in the unshaded four-meter boom sunspot chamber experiment. Camera 1 is a view from below the hung boom; Camera 2 and 3 are side views. These images are taken from the beginning of the experiment, before the boom had thermally deformed.

140°C to 20°C, then experiences another rapid transition to 80°C. This reflects the fact that the boom root was held still by the frame, while the tip was able to twist. When the boom tip twists, light from the IR sun lamp strikes different parts of the boom cross-section, changing both the temperature gradient and the shape of the boom.

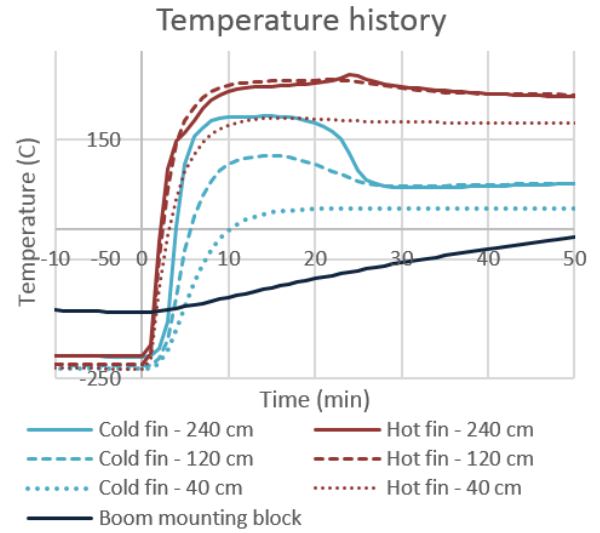


Fig. 7: Temperature histories at three stations on the boom. Several thermocouples were located at each station along the length of the boom; the thermocouples near the tip experiences a rapid change in temperature around 24 minutes into the experiment because the boom tip twisted to a new position.

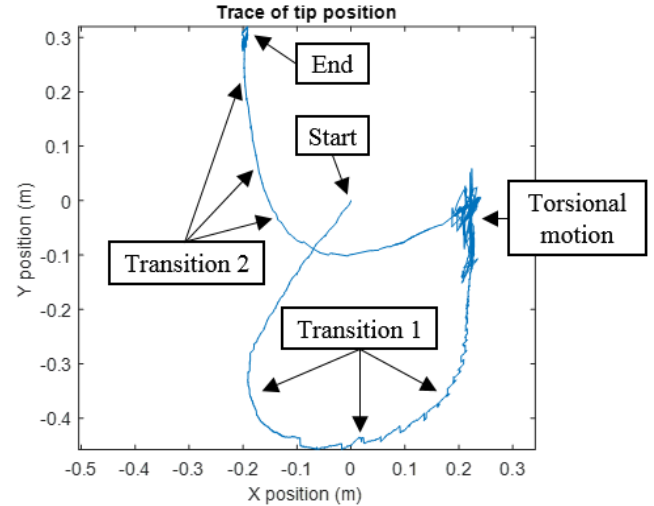


Fig. 8: The static and dynamic path of the boom tip in the laboratory frame. The sunspot lamp was located in the +X direction. The boom initially moves towards the predicted position for a boom in the space environment at a 45° sun incidence angle, then takes a range of other shapes.

Camera 1 captured the global boom shape, but did not image the tip. Fig. 10 shows three representative boom shapes from different times in the experiment.

3.2. Dynamic effects

After the initial deflection of Transition 1, the boom developed a torsional oscillation. The experiment was not designed with dynamics in mind, and there is consequently no special data product to tell us whether this motion could have been triggered by an outside source (for example, a truck driving by the building). The motion was dominated by a vibration at 0.8 Hz, a mode that was easily captured by the 30 Hz cameras. In the absence of atmospheric damping in the thermal vacuum chamber, the oscillation persisted for approximately 15 minutes between the first and second global shape transitions.

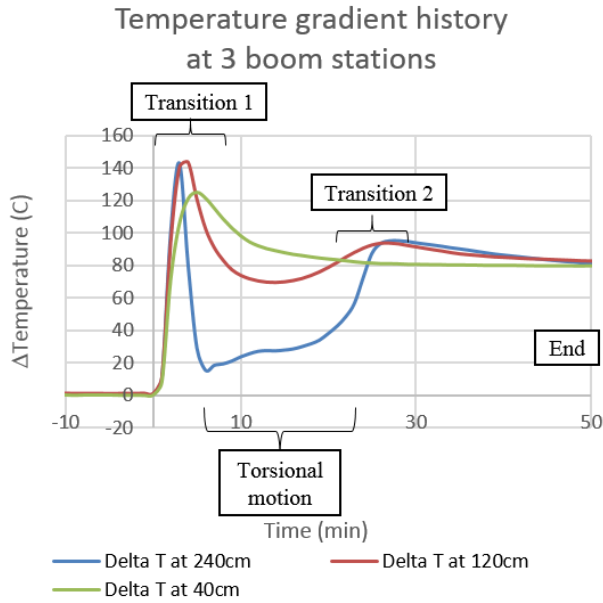


Fig. 9: The temperature difference between the hottest and coldest thermocouples at three stations along the length of the boom. Several thermocouples were connected to different positions in the boom cross-section at each station.

The torsional vibration of the boom was not captured by the thermocouples, even as noise- this may be because no thermocouples were located near the tip of the four-meter boom, where temperature oscillations would have been the greatest. Motion of 2-3 mm in magnitude was visible in the aluminum support frame during periods where the boom was oscillating.

4. Results analysis

The motivating analysis predicted that, in the space environment at 1 AU, the boom would experience a thermal gradient of 103°C and deform by 57 cm. The sunspot chamber conditions are not identical to the simulated conditions of that analysis, but the steady-state thermal gradient was 78°C and the steady-state deformation was 37 cm. The sunspot chamber experiment immediately established that thermal shape distortions of the predicted magnitude were possible and would directly impact the project.

It is interesting to compare the direction of displacement to the predicted direction. The predicted displacements for a boom rotated at 0°, 45°, and 90° to the sun are labeled in Fig. 11. The boom root in the experiment was fixed at 45° to the lamp, and the boom initially deforms towards the predicted shape of a boom under 45° incident light.

One question of both practical and academic interest is whether the observed vibrations are thermal flutter. It is possible that they are thermally induced vibrations from an initial overshoot of the equilibrium position, and also possible that they are due to an outside source of vibration. Thermal flutter is particularly interesting because it could develop from a small perturbation of a boom at equilibrium, and consequently could not be avoided by controlling the speed of spacecraft maneuvers or boom deployment.

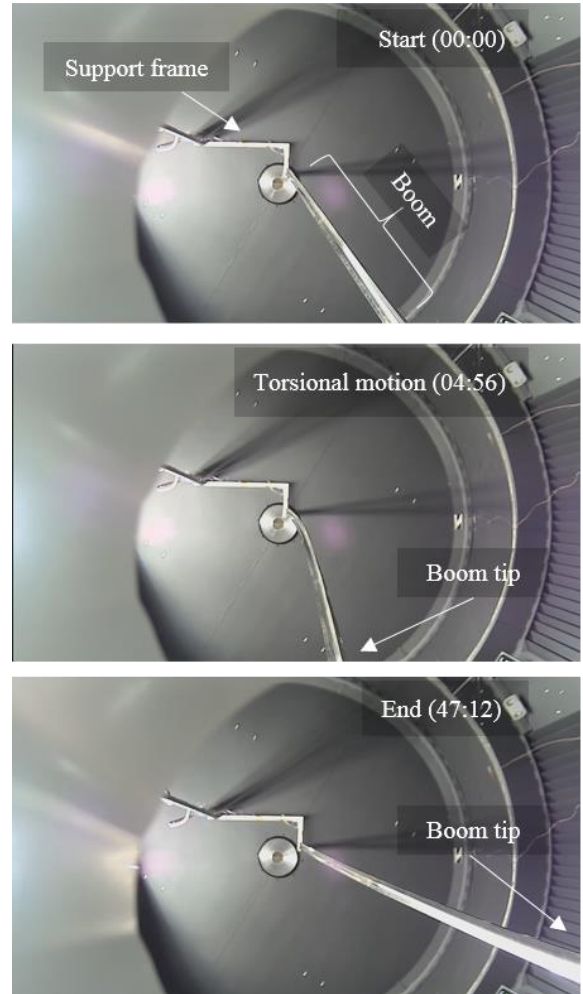


Fig. 10: A series of boom shapes, as seen from Camera 1. Times are noted in minutes and seconds. The wide field of view distorts straight lines near the edges of the image.

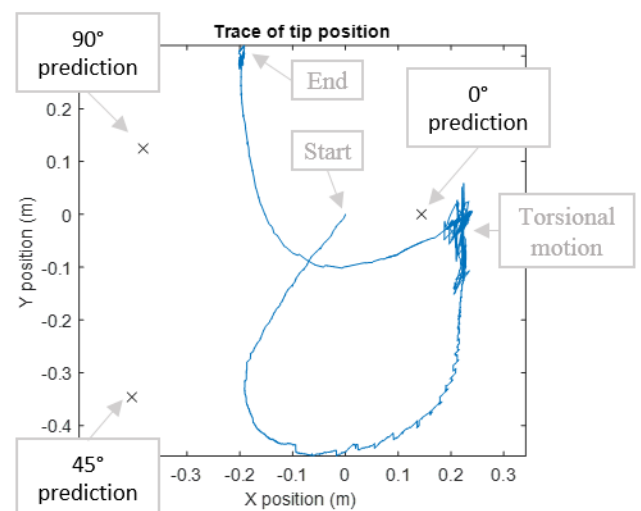


Fig. 11: The path of the unshaded boom tip in the sunspot experiment and the predicted boom tip positions for different on-orbit conditions. Results are presented in the lab frame, as if the IR array were station and the boom was rotated about the Z axis to different incident light angles.

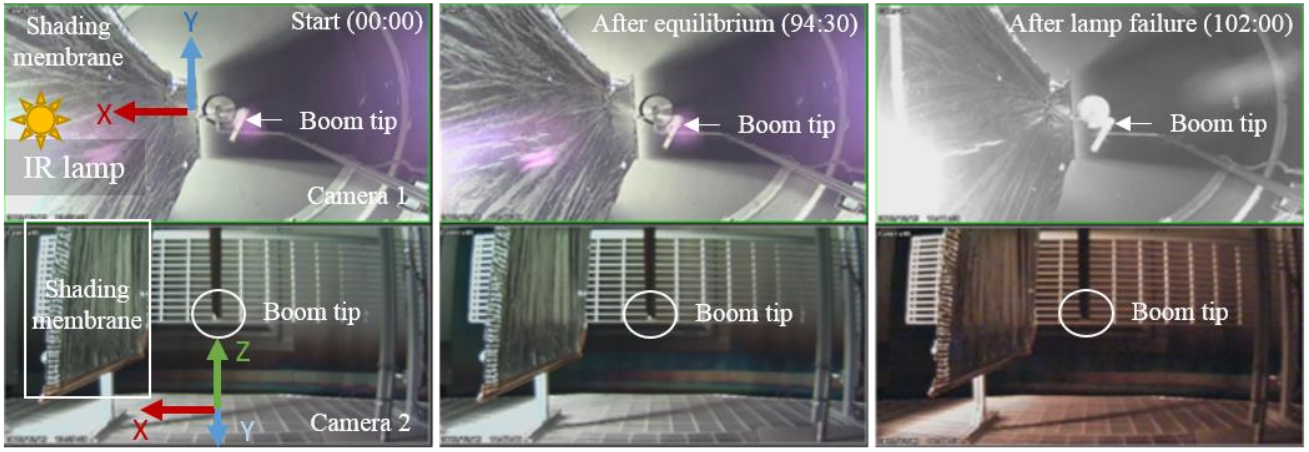


Fig. 12: Two camera views of the shaded boom experiment at the start, after thermal equilibrium, and after the IR lamps' abrupt shutoff. Times are noted in minutes and seconds. Refer to Fig. 13 for the camera arrangement.

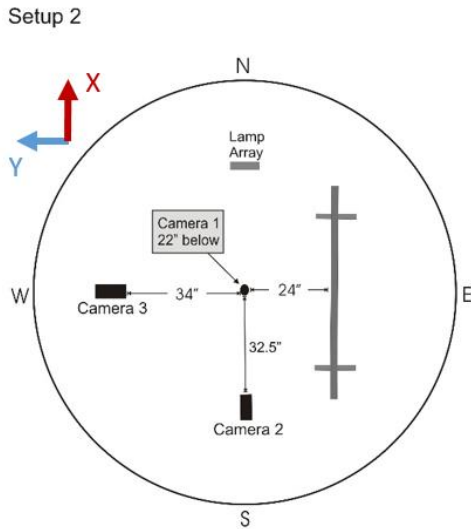


Fig. 13: Camera arrangement for the shaded experiment. View from above.

Thermal flutter is addressed analytically, experimentally and computationally in the literature. Thornton [6] gives an overview of thermal flutter and its historical study. He notes Beam's excellent study of torsional thermal flutter [7], which presents an analytical solution for thermal flutter in a slit circular cross-section.

Blandino [8] presented a finite element analysis with a coupled radiative thermal case for open and closed cross-section circular booms, specifically addressing bending flutter. To analyze a general case of thermal-elastic interaction in a non-circular boom with manufacturing defects, an ideal code would add internal radiative heat transfer to Blandino's approach.

There is no single explanation for the observed boom behavior, and no model has yet been pursued to describe the boom behavior to a higher level of precision. Some effects are simple to capture: the initially twisted as-manufactured shape of the boom, gravity, and the support frame, for example, would all be ordinary subjects for a nonlinear finite element stress analysis. In order to closely couple the stress analysis with radiative thermal analysis, however, a multiphysics tool is needed. Thermal Desktop and Abaqus/Standard were used to generate the motivating analysis, and iterations between these two pieces of software would be required to capture the transitions in the boom shape. Normally, Thermal Desktop is

used to generate a single temperature solution for the structure, which is then imposed on the Abaqus model. However, this initial temperature solution is not correct for the thermally deformed boom geometry, and the deformed geometry should be passed to Thermal Desktop for a new temperature solution at regular intervals. Several different temperature solutions would be required for every second of simulation time if the low-frequency torsional vibration is indeed thermal flutter.

4.1. Results for the shaded boom

After considering many possible solutions to this problem with the sail shape, the project chose to redesign the sail membrane so that the booms would be shaded by the sail membrane when the sail is fully deployed. Further thermal-structural analysis indicated that this would be an acceptable solution.

The experiment was repeated with a piece of sail membrane shading the boom from the IR lamps. Selected frames from this shaded experiment's video data are presented in Fig. 12, and the camera arrangement for this shaded boom test is shown in Fig. 13. Displacement of the boom tip was very small, and this followup experiment provided good support for the strategy of shading the booms with sail material. The boom tip path is shown in Fig. 14, alongside the path for the unshaded boom.

It is notable that the IR lamps suffered a failure after the shaded boom experiment had reached thermal equilibrium. This had a very small observable effect on the boom, but produced a small pendulum motion in the hanging membrane sheet, which has little thermal inertia and experienced rapid thermal contraction.

5. Conclusions

Carbon fiber composite booms experience substantially less thermal distortion than metallic booms, and trusses experience less than monolithic tapespring booms. As booms get longer, however, small thermal distortions will eventually add up to large geometric changes. In large deployable structures, and especially in very sparse, gossamer structures with limited heat conduction, it is important to include thermal distortion on the list of effects that should be investigated at every new length scale.

A multiphysics tool for truly coupled thermal-structural

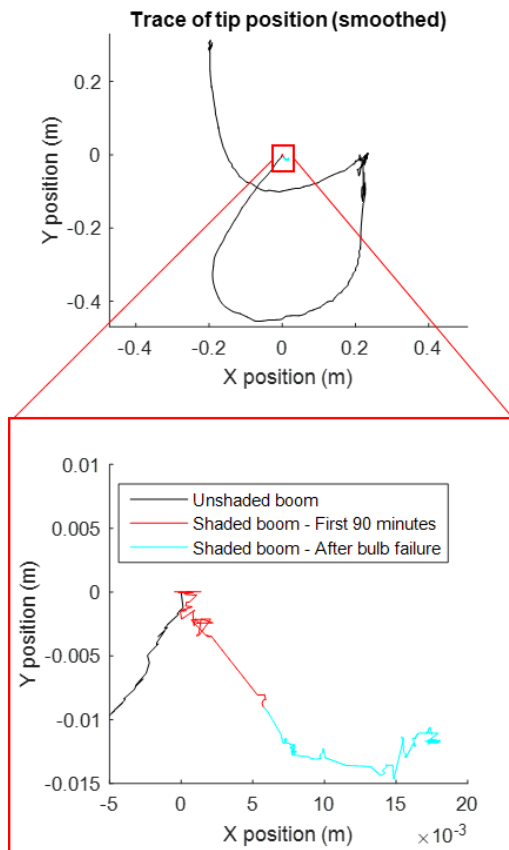


Fig. 14: The motion of the tip of the boom in the shaded case, compared with the unshaded boom movement. Data has been interpolated from a subset of video frames and smoothed with a moving average over three seconds; the maximum displacement of the shaded boom tip was 1 cm. The IR lamp array is located at +X in both cases.

analysis of large deployable structures would prove important as structures become larger. The authors hope that this paper demonstrates a clear application for software that can coordinate between nonlinear, large-displacement structural analysis and radiative ray-tracing analysis. The thermally induced displacements in this experiment changed the boom's temperature distribution, and simple sequential analysis would not predict the correct behavior in a single iteration between software products. A robust tool would ideally be capable of recalculating viewfactors and self-shading of a structure at intervals requested by the finite element solver. Existing software is close to providing this, and examples of special cases and bespoke solutions are numerous in the literature. Thermal Desktop, which was used to generate the thermal analysis results for NEA Scout, has a Component Object Model (COM) interface that can enable iterative optimization of telescope optics [9]. Thermal-fluid-structural interaction is the subject of decades of research and advanced modeling for aircraft and reentry decelerators [10], and the field of hypersonic flight probably provides the best example of a disciplined approach to thermal-structural interactions. Hypersonic flight analysis is more concerned with fluid thermodynamics than with radiative heat transfer, but there is a very large body of work from which to draw. To the authors' knowledge, Blandino's work [8] is the best example of the close coupling required between structural and thermal analysis for

this class of problem in spacecraft.

The NEA Scout project chose to change the sail design to reduce thermal gradients in the boom, and the current baseline design shades the TRAC booms from the sun with the sail membrane. The membrane's thermal expansion and contraction, which has a simple relationship to the sun incidence angle, is now the driving thermal-structural effect.

Acknowledgments

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